

Binary Black Hole Mergers from Planet-like Migrations

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ABSTRACT

If supermassive black holes (BHs) are generically present in galaxy centers, and if galaxies are built up through hierarchical merging, BH binaries are at least temporary features of most galactic bulges. Observations suggest, however, that binary BHs are rare, pointing towards a binary lifetime far shorter than the Hubble time. We show that, regardless of the detailed mechanism, all stellar-dynamical processes are insufficient to reduce significantly the orbital separation once orbital velocities in the binary exceed the virial velocity of the system. We propose that a massive gas disk surrounding a BH binary can effect its merger rapidly, in a scenario analogous to the orbital decay of super-jovian planets due to a proto-planetary disk. As in the case of planets, gas accretion onto the secondary (here a supermassive BH) is integrally connected with its inward migration. Such accretion would give rise to quasar activity. BH binary mergers could therefore be responsible for many or most quasars.

Subject headings: accretion disks – binaries: close – black hole physics – quasars

1. Introduction

Supermassive black holes (BH) are nearly ubiquitous in nearby galaxy nuclei (e.g. Ho 1999). These BHs formed very early, probably during the epoch of quasars, $z \gtrsim 2$, and are now largely dormant remnants of quasars. In the hierarchical picture

of structure formation, present day galaxies are the product of successive mergers (e.g. White 1996), and indeed there is evidence for many mergers in the high- z universe (Abraham et al. 1996). Hence, it appears almost inevitable that modern galaxies should harbor, or at least should have once harbored, multiple BHs that were collected during their merger history (Kauffmann & Haehnelt 1999).

BHs of mass $M \gtrsim 10^7 M_\odot$ will quickly find their way to the center of a merger remnant by dynamical friction. Logically, there are only three possibilities. First, BH pairs could merge to form a single, larger BH. Second, the pairs of BHs could form binaries that would remain at galaxy centers to this day. Finally, a third BH could also fall in, leading to a three-body interaction violent enough to expel any number of the three BHs from the galaxy (Begelman, Blandford, & Rees 1980). While in principle this means that all three holes could be ejected, in practice such a violent ejection event is unlikely unless the binary’s internal velocity is much higher than the escape velocity from the galaxy ($\gtrsim 2000 \text{ km s}^{-1}$); in this case, the binary would be in the late stages of merging anyway (see § 2). Since the broad lines of quasars are not often observed to be displaced from the narrow lines by such high velocities, the fraction of binaries with such high internal velocities cannot be large, and therefore triple ejection cannot be common. Hence, mergers generically produce BH binaries, and these binaries either merge on timescales short compared to a Hubble time, or they are present in galaxies today.

Observationally, there is evidence only for a few massive BH binaries (e.g., Lehto & Valtonen 1996) and in none of these cases is the evidence absolutely compelling. Theoretically, it has proven difficult to construct viable merger scenarios for these BH binaries. Here we first review this difficulty of driving the merger by the stellar-dynamical means that are discussed in the literature. We then propose a gas-dynamical alternative.

2. Near Impossibility of Stellar Dynamics-Driven Mergers

If a BH binary could (somehow) be driven to a sufficiently small orbit, then gravitational radiation would increasingly sap energy from the system and so engender a merger. For a circular orbit with an initial velocity v_{gr} , the time T to a

merger due to gravitational radiation is given by

$$v_{\text{gr}} = c \left(\frac{5}{256} \frac{GM_{\text{tot}}^2}{\mu T c^3} \right)^{1/8} = 3400 \text{ km s}^{-1} \left(\frac{M_{\text{tot}}^2 / \mu}{8 \times 10^8 M_{\odot}} \right)^{1/8} \left(\frac{T}{10 \text{ Gyr}} \right)^{-1/8} \quad (1)$$

where $M_{\text{tot}} = M_1 + M_2$ is the total mass, $\mu = M_1 M_2 / M_{\text{tot}}$ is the reduced mass, and where we have normalized to the case $M_1 = M_2 = 10^8 M_{\odot}$. Note that for fixed total mass, the equal-mass case gives a lower limit on this required velocity, and that the result depends only very weakly on the total mass.

However, as we now show it is almost impossible to achieve this velocity by any conceivable stellar-dynamical process. The basic problem is that when the orbital velocity v_{orb} is about equal to the stellar velocity dispersion $\sigma \sim 200 \text{ km s}^{-1}$, the total mass in stars within a volume circumscribed by the BH orbital radius ($a \sim 5 \text{ pc } M_{\text{tot}} / 10^8 M_{\odot}$) is about M_{tot} . If all of these stars were expelled from the BH binary at speed $v_{\text{orb}}(M_2/M)^{1/2}$ (Rajagopal & Romani 1995 and references therein) the binding energy of the binary would increase by only a factor $\sim e$. However, to get from a virial velocity of $\sim 200 \text{ km/s}$ to v_{gr} (eq. 1), would require $N_e \sim 6$ e -foldings in binding energy. Hence, the binary will clear out a hole in the stellar distribution, and dynamical friction will be shut down (Quinlan 1996; Quinlan & Hernquist 1997).

The most efficient conceivable process to rejuvenate the orbital decay would be to equip the binary with an intelligent “captain”. Like a fisherman working in over-fished waters, whenever the captain saw that the binary was running out of stars to expel, she would steer the binary to the densest unexploited region of the galaxy. To effect the merger, this would mean systematically moving through and expelling all the stars within a region containing about $N_e M_{\text{tot}}$ in stars. For a galaxy with an r^{-2} density profile, this implies expelling all the stars within a radius $r = N_e GM_{\text{tot}} / 2\sigma^2 \sim 60 \text{ pc}$, where we have made the evaluation for $M_{\text{tot}} = 2 \times 10^8 M_{\odot}$ and $\sigma = 200 \text{ km s}^{-1}$.

The real difficulty of the captain’s work is best understood by considering the last e -folding before gravitational radiation can take over. For $v_{\text{orb}} \gg \sigma$, the cross section for hard interactions (including gravitational focusing) is $\lesssim \pi a^2 v_{\text{orb}} / \sigma$. If each incident particle is expelled with speed $v_{\text{orb}}(M_2/M)^{1/2}$ (Rajagopal & Romani 1995), then the binding energy E_b decays at $d \ln E_b / dt \sim 2\pi a^2 v_{\text{orb}} \rho / M = G\rho P$, where P is the period, and ρ is the local density. The last e -folding alone would require a time $t \sim [G\rho(r)P]^{-1} \sim 2\pi(r/\sigma)^2 / P \sim 2 \text{ Gyr}$, where we have assumed $r \sim 30 \text{ pc}$ and our other canonical parameters. Thus, even with the captain’s careful guidance, the full

merger requires a large fraction of a Hubble time. Moreover, comparing this decay rate with the standard formula for the decay of translational energy E_t (Binney & Tremaine 1987) yields,

$$\frac{d \ln E_b}{dt} \lesssim 0.1 \left(\frac{\sigma}{v_{\text{orb}}} \right)^3 \frac{d \ln E_t}{dt}. \quad (2)$$

That is, $d \ln E_b / d \ln E_t \lesssim 10^{-4}$, so that the binary would be driven by dynamical friction back to the center of the Galaxy before it had completed 10^{-4} of an e -folding of energy loss. Hence, the captain would have to initiate 10^4 “course changes” in the last e -folding alone. Since the “captain” must in fact be some random process, the only source of such “course changes” is brownian motion due to continuous interaction with other compact objects. However, for stars of mass m in an r^{-2} profile, the range of such Brownian motion is $\Delta \ln r \sim m/M_{\text{tot}}$, i.e., too small by several orders of magnitude. In contrast to ordinary Brownian motion, the present system has an “external” energy source, the binary’s binding energy. However, it follows from equation (2) that even if all of this donated energy were acquired by the binary’s transverse motion, the brownian motion would be only slightly augmented. In any event, most of the donated energy goes to the stars, not the binary. Infall of globular clusters might well give the binary an occasional jolt, but these would be far too infrequent to drive the merger. In brief, any sort of mechanism to drive a merger by ordinary dynamical friction, no matter how contrived, is virtually ruled out.

The only loophole to this argument is that we have assumed circular binary orbits. If an instability existed that systematically drove the BH binaries toward eccentricity $e \rightarrow 1$ orbits, then either the binaries would suffer enhanced gravitational radiation (for a fixed semi-major axis) or could even merge in a head-on collision. Fukushige, Ebisuzaki, & Makino (1992) first suggested such an instability based on the following qualitative argument: dynamical friction is more effective at low speeds than high speeds and hence, in the regime where the ambient particles interact with the binary mainly by encounters with its individual members ($v_{\text{orb}} \lesssim \sigma$), the binary would suffer more drag at apocenter than pericenter, tending to make the orbit more eccentric. Fukushige et al. (1992) presented numerical simulations that gave initial support to this conjecture. There are, however, two reasons for believing that this effect cannot drive mergers. First, several groups have conducted more sophisticated simulations, and these do not show any strong tendency for $e \rightarrow 1$ (Makino et al. 1994; Rajagopal & Romani 1995; Quinlan & Hernquist 1997). Second, once the binary entered the regime $v_{\text{orb}} \gg \sigma$, the ambient particles would interact with

the binary as whole, and so there is no reason to expect any drive toward high eccentricities. Hence, while this loophole is not definitively closed, neither does it look particularly promising.

3. Gas Dynamical Solution

Begelman, Blandford & Rees (1980) were the first to suggest that gas infall may “lead to some orbital evolution”. But, at the time it was not clear that all other mechanism to overcome the BH hangup would most likely fail.

To resolve the above dilemma, we suggest that gas dynamics play the decisive role in orbital decay, forcing the secondary BH to “migrate” in toward the primary in a manner analogous to the migration of planets. Such migration has been proposed to account for the discovery of jovian-mass and superjovian-mass planets at $\lesssim 1$ AU from solar-type stars, while it is generally believed that such massive planets can only be created several AU from the stars (Trilling et al. 1998). Artymowicz & Lubow (1994, 1996) simulated interactions between moderately unequal-mass binaries and accretion disks, which is more directly relevant to the present case than extreme-ratio (planetary) systems. They did not follow the orbital evolution as has been done in more recent work on planets, but only evaluated the instantaneous effect of the torques. They found a migration to higher eccentricities was a larger effect than migration to smaller orbits. Regardless of which effect dominates, one would expect the final merger to be from circular rather than radial orbits: if the binary is driven toward radial orbits, its emission of gravitational radiation near pericenter will eventually pull in the apocenter of the orbit, decoupling the binary from the disk and allowing the gravitational radiation to circularize the orbit before final coalescence.

For migration to work, the galaxy merger that creates the BH binary must eventually dump at least M_2 worth of gas into the inner ~ 5 pc of the merger remnant where the binary coalescence has gotten “hung up”. Whether this happens on timescales short compared to a dynamical time at 5 pc ($\sim 10^7$ yr), leading to tremendous gas densities and ensuing rapid star formation (Taniguchi & Wada 1996), or whether the gas accumulates over a longer timescale and so does not trigger a starburst, the basic scenario will be the same.

There is every reason to expect mergers effect such a gas accumulation. First,

quasars must gorge themselves on gas to reach their present size. Hence, regardless of whether our picture of binary mergers is correct, this much gas must find its way to central BHs. Second, there is substantial evidence that many quasars are in either recent merger remnants or at least significantly disturbed galaxies (Kirhakos et al. 1999 and references therein). Hence, it seems likely that mergers are the most efficient means to drive gas to the center. Third, many spiral bulges and ellipticals have cuspy profiles populated by metal rich stars whose total mass is comparable to that of their massive BHs (van der Marel 1999). Thus, it must be possible to funnel huge amounts of gas to the centers of galaxies.

In planet migration, the migration timescale is similar to the accretion timescale for growing the planet because the two processes are governed by the same phenomena, gravitational torques and dissipation (Trilling et al. 1998; A. Nelson 1998, private communication). We expect the same to be true of migration of BH binaries. Thus, there should be a grand accretion disk around the primary with a “gap” opened up by the secondary. Material should be transported across this gap to a second, smaller accretion disk surrounding the secondary BH. The total energy liberated by this smaller accretion disk should be $\sim \epsilon M_2 c^2 \sim 2 \times 10^{61} (M_2 / 10^8 M_\odot)$ ergs, where we have taken the efficiency to be $\epsilon = 0.1$, producing a quasar-like appearance during this phase.

4. Discussion

While our suggestion, driven by the lack of alternatives, makes few unambiguous predictions, it does open several lines of investigation that could help test and flesh out our picture.

First, merging binaries would appear very much like quasars, since our picture of the migrating secondary is essentially identical to the standard picture of a quasar. The one difference is that the jet from a migrating BH could precess if the orbit of the secondary were substantially misaligned relative to the accretion disk. At present, however, we have no method of estimating how often significant misalignment should occur.

Second, the redshift of the broad lines from a migrating BH’s accretion disk should be offset from the redshift of the host galaxy (as traced perhaps by the narrow lines). Since the migration probably accelerates with time, most migrating

quasars should have $v_{\text{orb}} \sim \sigma$. Nevertheless, some should have substantially higher offsets, and measuring the distribution of these offsets would allow one to trace the migration process. However, if no offsets were observed, this would not in itself rule out our hypothesis. It could be, for example, that migrating binaries in merger remnants are preferentially buried in a larger, roughly spherical cloud of dusty gas. In this case, they would have more similarity to ultra-luminous infrared galaxies (ULIRGs) than to quasars, and the line centers of their emission would be at the galaxy velocity, not that of the secondary.

Third, it is at least possible that one would see two broad-line systems, one from the primary and one from the secondary. Since broad lines are by definition broad ($\gtrsim 3000 \text{ km s}^{-1}$), the existence of two systems would not easily be recognized for $v_{\text{orb}} \sim \sigma$. However, distinct peaks might be discernible when the BHs were closer to merger. On the other hand, it may be that the major supply of gas lies outside the orbit of the secondary, and hence the primary does not generate a significant broad-line region.

Fourth, it will be important to carry out simulations to determine whether the gas dissipation timescale is short enough for the accreting material to follow the binary inward. This is certainly the case for the simulations that have been done for extreme mass-ratio (planetary) systems, but needs to be checked for the less extreme case also.

Finally, we suggest that migrating BH binaries may simply *be* the quasars, or at least most of them. They have the same integrated energy output as quasars, they have the same accretion-disk fuel source as quasars, and like quasars, they turn on in the wake of mergers. It may be easier to move gas inward from $\sim 5 \text{ pc}$ scales for a binary BH than for a single BH because the binary would excite spiral density waves in the grand accretion disk and so augment viscous drag. Accretion in the inner disk around the secondary might also be easier than for an isolated BH because of the tidal effects of the primary. If this hypothesis is correct, then quasars should generically show offsets between the centers of their broad and narrow lines with a root mean square of $\sim (2/3)^{1/2} \sigma$.

Acknowledgements: We thank Andy Nelson for valuable discussions. A.G. thanks the Max-Planck-Institut für Astronomie for its hospitality during a visit when most of work of this Letter was completed. His work was supported in part by grant AST 97-27520 from the NSF.

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